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Project Title: Diagnosis of the Kinematics and Dynamics of Rapidly Developing Maritime Cyclones

PROGRESS REPORT

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The following tasks relating to Mr. Gary Lackmann's doctoral dissertation research have been completed: (1) identification of planetary-scale flow signatures preceding and coincident with explosive western North Atlantic cyclogenesis; (2) examination of the relationship between the large-scale flow, the evolution of upper troughs, and the degree of surface development during ERICA; (3) investigation of the life cycles of upper-tropospheric troughs during ERICA; (4) analysis of factors modulating surface development; (5) application of high-resolution diagnostics illustrating upper-tropospheric trough genesis and evolution.

1. Identification of planetary-scale flow signatures preceding and coincident with explosive western North Atlantic cyclogenesis

The planetary-scale flow exhibits robust characteristic signatures in association with rapid maritime cyclogenesis in the western North Atlantic region, suggesting strong downscale control or modulation of this process. Observations indicate that intense western North Atlantic (WNA) cyclogenesis tends to occur during periods of amplified large-scale flow. This motivates identifying typical large-scale flow anomalies accompanying WNA cyclogenesis and establishing dynamical connections between these anomalies and WNA cyclogenesis. Characteristic features of the large-scale flow, emerging from a composite of 43 explosive WNA cyclone events, include: (i) a strong North Pacific trough and enhanced North Pacific jet; (ii) ridging over western North America; (iii) an upper-tropospheric jet streak in northwesterly flow east of the western North American ridge axis; and (iv) an amplifying trough/ridge couplet over eastern North America and the western North Atlantic. The relationship between the large-scale flow and WNA cyclogenesis involves the "steering" of embedded troughs by the upper-level flow and the amplification of upper troughs in northwesterly flow downstream of the western ridge axis. With ridging (troughing) over western (eastern) North America, upper troughs embedded in the main belt of westerlies cross the East Coast far enough south to pass over the Gulf Stream. Moreover, this large-scale pattern is conducive to amplification of the upper troughs themselves.

2. Examination of the relationship between the large-scale flow, the evolution of upper troughs, and the degree of surface development during ERICA

In order to examine the relationship between the large-scale flow and western North Atlantic cyclogenesis in detail, the three-month ERICA period (December 1988 - February 1989) is scrutinized for the existence of quasi-recurrent "regimes," based on the degree of both upper-level trough and surface cyclone activity. Using this criterion, twelve periods representing three types of behavior are identified. Periods characterized by frequent, vigorous upper-trough transits into the western North Atlantic region and active low-level cyclogenesis are labelled "active cyclogenetic" (AC); periods with vigorous upper-trough activity but little surface response are labelled "active quiescent" (AQ); and periods with weak activity at all levels are labelled "inactive quiescent" (IQ). Composites are constructed for each of these three types of behavior. The AC type is characterized either by a western ridge, an eastern trough, and a strong jet over eastern North America, or by phasing disturbances in confluent upper-level flow. The AQ type is characterized by a pattern similar to that of the AC type, but tends to show upper-level disturbances to be located farther north as they cross the East Coast. The IQ type is characterized by a western trough and an eastern ridge, with a strong North Atlantic jet and confluent upper-level flow.

Because the upper troughs during AC periods are similar in intensity to those during AQ periods, the larger lower-tropospheric response presumably is due to stronger baroclinicity or to lower static stability, both of which are related to the proximity of the trajectories of the upper troughs to the Gulf Stream. In order to quantify the potential for lower-tropospheric response, a growth rate parameter is formulated that diagnoses the potential for growth through baroclinic energy conversion; calculations of this parameter suggest that the lower-tropospheric environment is more favorable for cyclogenesis over the western North Atlantic during AC compared with AQ periods.

3. Investigation of the life cycles of upper-tropospheric troughs during ERICA

In order to understand the dynamical links between the large-scale flow and individual cyclone events, seventeen cases during the three-month ERICA period are selected for detailed study. Examination of these cases reveals several common signatures during the evolution of mobile upper-tropospheric troughs occurring over the western North Atlantic region. Nine of the seventeen cases exhibit initially elongated upper-level vorticity features that compact into more circular troughs. Other cases are characterized by lateral interactions between two or more upper troughs, the fracture of a pre-existing trough, and the passage of nondeveloping troughs into the cyclogenetically favorable coastal region. Compacting upper troughs are associated with the strongest ERICA cyclogenesis events (IOP 2 and IOP 4). This evolution occurs as an initially elongated upper disturbance amplifies through the action of frontogenetical vertical circulations in northwesterly flow, and subsequently "compacts" into a more circular disturbance in diffluent flow. Upon crossing the East Coast, these upper troughs interact vigorously with lower-tropospheric disturbances, resulting in strong cyclogenesis.

4. Analysis of factors modulating surface development

The strength of lower-tropospheric development accompanying the seventeen vigorous upper-level troughs varies from very weak to the extreme event of IOP 4. Factors that modulate the lower-tropospheric response to the approach of upper-level troughs have been isolated diagnostically. In addition to troposphere-deep static stability, a dynamically motivated coupling index is proposed in order to diagnose the degree to which upper-level troughs exert a dynamical influence on the lower troposphere. This index is a function of the spatial scale and shape of a disturbance, the depth of the troposphere, and local values of static stability, inertial stability (local rotation rate), and baroclinicity (vertical wind shear). The coupling index proves to be a useful discriminator of lower-tropospheric cyclogenetic response in most cases, although there are several for which it is inconclusive. Evidently, in some cases, factors not accounted for in the coupling index may have a strong impact on surface development. These factors include moisture availability, the vertical extent of the antecedent lower-level vorticity feature initially present along the path of the upper-level trough, and the speed of the upper-level trough (affecting the time allowed for vertical coupling). Determining the optimal combination of factors and elucidating their dynamical role is deferred to future research.

5. Application of high-resolution diagnostics illustrating upper-tropospheric trough genesis and evolution

Further diagnostic results include calculation of vorticity budgets, a variety of representations of frontogenesis, and the deformation field represented in the form of dilatation axes. The psi-vector technique of Keyser and colleagues recently has been adopted to display vertical circulations in frontal regions. Such diagnostics are applied to the high-resolution (1.125° x 1.125°) ECMWF datasets for the seventeen selected cyclogenesis events. Results of the vorticity budgets highlight the importance of tilting in generating vorticity for cases of compacting upper-level troughs. Diagnostic calculations reveal the importance of frontogenetical vertical circulations in lowering the tropopause along the upper front; synoptic-scale deformation then acts to compress this elongated potential vorticity anomaly prior to surface cyclogenesis.

In addition to the frontogenesis and vertical circulation diagnostics, a kinetic energy budget is implemented following the methodology developed by Orlanski and Katzfey. This form of the energy budget is applied to the seventeen cyclogenesis events during the ERICA period, allowing evaluation of interactions between individual precursor disturbances (i.e., mobile upper-level troughs) and the time-averaged flow. This so-called "local" approach has the advantage of eliminating the need to define a storm volume over which to calculate the energetics and thus removes the arbitrary dependence of the results on boundary fluxes. Results indicate an important role for Reynolds stress terms (quantifying interactions between the disturbance and vertical and horizontal shears in the time-averaged flow) early in the development of compacting upper-level disturbances. Furthermore, an apparently characteristic signature of the disturbance velocity field in relation to the time-mean deformation pattern for periods of northwesterly flow over central North America during the ERICA

period has been identified. This signature is diagnosed to be especially conducive to the growth of disturbance kinetic energy through the Reynolds stress term in a localized region, suggesting a new mechanism for jet-streak formation and maintenance.

Publications Supported by ONR

1. Refereed papers

Evans, M. S., D. Keyser, L. F. Bosart, and G. M. Lackmann, 1994: A satellite-derived classification scheme for rapid maritime cyclogenesis. *Mon. Wea. Rev.*, **122**, 1381–1416.

Loughe, A. F., C.-C. Lai, and D. Keyser, 1995: A technique for representing three-dimensional ageostrophic circulations in baroclinic disturbances on limited-area domains. *Mon. Wea. Rev.*, **123**, 1476–1504.

2. Conference preprints

Cammas, J.-P., D. Keyser, G. Lackmann, and J. Molinari, 1994: Diabatic redistribution of potential vorticity accompanying the development of an outflow jet within a strong extratropical cyclone. Proceedings, *International Symposium on the Life Cycles of Extratropical Cyclones*, Vol. II, S. Gronas and M. A. Shapiro, Eds., Geophysical Institute, University of Bergen, Norway, 403–409.

Cammas, J.-P., D. Keyser, J. Molinari, and G. Lackmann, 1994: Intensification of an interior potential vorticity maximum in the ECMWF analysis and its subsequent interactions with an upper-level jet. Preprints, *Tenth Conference on Numerical Weather Prediction*, Portland, OR, Amer. Meteor. Soc., 514–517.

Keyser, D., 1994: On the representation and diagnosis of frontal circulations in two and three dimensions. Proceedings, *International Symposium on the Life Cycles of Extratropical Cyclones*, Vol. I, S. Gronas and M. A. Shapiro, Eds., Geophysical Institute, University of Bergen, Norway, 193–207 **(invited paper)**.

Lackmann, G. M., D. Keyser, and L. F. Bosart, 1994: On the evolution of mobile upper-tropospheric troughs preceding western North Atlantic cyclogenesis during ERICA. Proceedings, *International Symposium on the Life Cycles of Extratropical Cyclones*, Vol. II, S. Gronas and M. A. Shapiro, Eds., Geophysical Institute, University of Bergen, Norway, 251–256.

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Hanley, D. E., J. Molinari, and D. Keyser, 1995: A study of the role of vertical shear in tropical cyclone development. Preprints, *Twenty-First Conference on Hurricanes and Tropical Meteorology*, Miami, FL, Amer. Meteor. Soc., 71–73.

3. Doctoral dissertation

Lackmann, G. M., 1995: Life cycles of mobile upper troughs and maritime cyclones during ERICA. Ph.D. thesis, Department of Atmospheric Science, State University of New York at Albany, 318 pp.